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# USML-1 MICROGRAVITY
# GLOVEBOX EXPERIMENT #1
# PASSIVE ACCELEROMETER SYSTEM


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# Glovebox experiment #1: Final Report
# Passive accelerometer system: Measurements on STS-50 (USML-1)

The passive accelerometer system (PAS) is a simple moving ball accelerometer capable of measuring the small magnitude steady relative acceleration that occurs in a low earth orbit spacecraft due to atmospheric drag and the earth's gravity gradient. The accelerometer can be used when the spacecraft continuously rotates during the orbit such that some line of reference in the craft always points along the vector connecting the earth's mass center with the spacecraft mass center. PAS was used successfully on the first United States Microgravity Laboratory (USML-1).

### *Introduction*

The passive accelerometer system (PAS) was designed to measure the quasi-steady residual acceleration caused by a combination of atmospheric drag effects and the gravity gradient. This acceleration should be on the order of $10^{-6}$g or less and is difficult to record accurately using conventional accelerometers. The acceleration is obtained indirectly by recording the motion of a small proof mass along an oriented tube filled with liquid. The trajectory and speed of the proof mass can then be used to find the residual acceleration indirectly using Stokes' Law [1-3]. Since the walls of the tube used in PAS affects the motion of the ball, the Ladenburg-Faxen-Francis [4] correction to Stokes' Law is applied.

### *Apparatus and operation*

The PAS consists of a 2 cm diameter glass tube with a wall thickness of 2mm. The tube is filled with water and contains a 0.2 cm diameter steel ball. At one end of the tube is a fill and pump port with a high vacuum stopcock valve. The tube is enclosed in a clear LEXAN tube. The LEXAN tube is sealed with two endcaps and is attached to modified camera tripod head to allow for a full range of orientations. The tripod head is mounted onto a steel plate which is backed with Velcro strips to allow for easy mounting to surfaces in the spacecraft. A pencil magnet is used to reposition the ball inside the tube.

A typical operation of PAS would be as follows:

The accelerometer tube is oriented such that the tube axis is approximately parallel to the estimated acceleration direction. The magnet is then used to position the proof mass at the end of the tube. The starting position of the proof mass is then recorded and a timer is started. At 1-2 minute intervals the payload specialist checks that the trajectory of the proof mass lies along the tube axis and records the time and position of the proof mass. If the angular deviation of the ball's trajectory from the tube axis is greater than 10 degrees, the tube is repositioned such that its axis lies along the trajectory of the proof mass. Each run is complete when the proof mass has traversed the length of the tube. Note that the attitude motion of the spacecraft must be one for which a quasi-steady gravity gradient acceleration is expected.

### *Results*

This section summarizes accelerometer readings made on STS-50 (USML-1) with PAS (Flight Deck) and OARE (Orbital Acceleration Reserach Experiment) on MET days 2&3, and a single data point from PAS taken near the Crystal Growth Furnace (CGF) on day 6. The PAS data represents an average over 8 measurements. Both the Flight Deck and OARE data are extrapolated to the CGF location. Both OARE and PAS data indicate that besides the gravity gradient and atmospheric drag effects, for the USML-1 mission there was an additional contribution to the quasi-steady residual acceleration vector. It contributed, approximately, an additional 0.5 μg acceleration along the negative x-direction (body coordinates see Fig. 1). This cannot be entirely accounted for by the Flash Evaporation System (FES)[1]. Note that the frame of reference of the residual accelerations presented here is taken to be the spacecraft frame[2] and that the coordinate system refers to the "Orbiter body coordinates" (see Fig. 1).

All acceleration vectors are represented in the form **a** = $(a_x, a_y, a_z)$, where the components of **a** represent the projections of the total acceleration vector onto the x-,y- and z-body axes.

### *Flight deck accelerations*

Table 1. Flight deck data, days 1-5

| U [cm s$^{-1}$] | **acceleration** [cm s$^{-2}$] | **acceleration** [g] |
|---|---|---|
| $2.43 \times 10^{-2}$ | $4.34 \times 10^{-3}$ | $4.43 \times 10^{-6}$ |
| $2.52 \times 10^{-2}$ | $4.48 \times 10^{-3}$ | $4.57 \times 10^{-6}$ |
| $2.73 \times 10^{-2}$ | $4.87 \times 10^{-3}$ | $4.97 \times 10^{-6}$ |
| $2.49 \times 10^{-2}$ | $4.44 \times 10^{-3}$ | $4.53 \times 10^{-6}$ |
| $2.38 \times 10^{-2}$ | $4.23 \times 10^{-3}$ | $4.32 \times 10^{-6}$ |
| $2.57 \times 10^{-2}$ | $4.58 \times 10^{-3}$ | $4.67 \times 10^{-6}$ |
| $2.54 \times 10^{-2}$ | $4.53 \times 10^{-3}$ | $4.62 \times 10^{-6}$ |
| $2.56 \times 10^{-2}$ | $4.58 \times 10^{-3}$ | $4.67 \times 10^{-6}$ |

Maximum deviation in values 12% (occurred on same day)

Readings were taken in Flight deck from days 1-5, and on remaining days measurements were made in the spacelab. As can be seen from the table below, these readings produced consistent data and the PAS appeared to work best here. The flight deck readings form the best data set. Only the readings taken near the CGF in spacelab produced a usable measurement. The remaining readings in spacelab were either disturbed too frequently to yield useful data or the excursion of the ball was too small. Table I gives the ball velocities and associated acceleration for the flight deck.

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[1]R. Blanchard, OARE STS-50 Flight Data, final report, December, 1992.

[2]See attached article by Rogers, Alexander and Matisak: A Note on the frame of reference for Orbiter acceleration measurements

At the flight deck location, the direction of the acceleration was chiefly along the positive x-body axis of the orbiter. This is consistent at this location with the expected domination of the gravity gradient acceleration. Since we know the variation of the gravity gradient acceleration as a function of location [2,3] the flight deck results can be extrapolated to the CGF location.

***Accelerations at the CGF location (extrapolated)***

The acceleration, **a***, calculated from extrapolated PAS Flight Deck data (MET days 2&3) is

$$\mathbf{a}^* = (-0.57, 0.14, -0.46)\ \mu g$$

This vector is illustrated in Fig. 2, and shows that the vector is tilted away from the CGF axis by about 15° in the y-z plane. The tilt direction is toward positive y. In the x-z plane the vector is tilted away from the CGF axis by about 50° toward negative x. The PAS measurement is compared to the two sets of OARE data given below. Each set has a mean vector and a maximum and minimum magnitude vector. The corresponding vectors are shown in Figs. 3-8.

Table 2. OARE data

| set#1, FES off | Mean [μg] | Max [μg] | Min [μg] |
|---|---|---|---|
| $\mathbf{a}_x$ | -0.23 | 0.1 | -0.5 |
| $\mathbf{a}_y$ | 0.12 | 0.4 | -0.1 |
| $\mathbf{a}_z$ | -0.75 | -0.3 | -1.0 |

| set#2 , FES on | Mean [μg] | Max [μg] | Min [μg] |
|---|---|---|---|
| $\mathbf{a}_x$ | -0.6 | -0.2 | -0.8 |
| $\mathbf{a}_y$ | 0.12 | 0.4 | -0.1 |
| $\mathbf{a}_z$ | -0.4 | -0.1 | -0.65 |

The reading taken with PAS near the CGF yielded a magnitude of approximately 0.6 μg. The orientation of the tube was directed primarily along the negative x-axis, and tilted in toward the CM about 15 degrees (this is compatible with the (x,y) components of the acceleration measured in the Flight Deck and indicates that the gravity gradient component in the negative x-direction was augmented by an additional acceleration of about 0.5 μg magnitude, and that the drag was much smaller than 0.5 μg. The question is how much smaller? Here the PAS measurement made near CGF is inconclusive. The ball excursion distances were small, 1 cm, compared to 7cm in the Flight Deck. The reason for this was that the intermittent vernier firings disturbed the ball motion at 3-5 minute intervals. Only one reliable reading was obtained near the CGF and while the magnitude is a reliable measure, the orientation results are questionable when one considers the ball radius is such that excursions of 4-6 cm are necessary to distinguish the orientation of the residual acceleration vector. (A back-up accelerometer tube with a larger radius ball that would have moved further between vernier firings was available. Unfortunately, circumstances did not permit transmittal of a request for the tubes to be swapped).

***Remarks***

• The PAS data and the OARE data both indicate that the net acceleration vector was not generally aligned with the CGF axis (see Figs. 3-8). If the drag had been 1 μg or greater then the residual vector would have been closer to the CGF axis, although atmospheric density fluctuations will cause continuous orientation changes.

• Since the PAS location was displaced from the CGF along the x-axis the resultant vector would be expected to be oriented differently from the acceleration vector at the CGF due to gravity gradient effects.

• The resultant vector at CGF would only have lined up with the CGF axis if the drag had been $10^{-6}$ g. Had this been the case PAS would also have shown this orientation since drag would have dominated the gravity gradient. However, two things are apparent from CGF and OARE measurements:

• The gravity gradient acceleration along the x-axis is augmented by a 0.5 μg acceleration acting along negative x. This has the effect of tilting PAS away from the CGF axis.

• According to OARE and the PAS Flight Deck measurements, the actual drag was about 0.5μg and OARE shows that at times it was lower. Under these conditions (even without the extra x-acceleration) the resultant acceleration vector would not have been aligned with the furnace axis but would be tilted at 25 degrees from the CGF toward positive y.

Acknowledgments
The enthusiastic participation of the USML-1 crew and NASA's Glovebox support team is gratefully acknowledged.

***References***

[1] L. D. Landau and E. M. Lifshitz, Fluid Mechanics, Course of Theoretical Physics, Volume 6 (Pergamon, Oxford, 1979) p. 63.
[2] J.I.D. Alexander, and C. A. Lundquist, AIAA Journal 26 (1988) 34.
[3] J.I.D. Alexander, and C. A. Lundquist, J. Astr. Sci. 35 (1987) 193.
[4] A. W. Francis, Physics 4 (1933) 403.

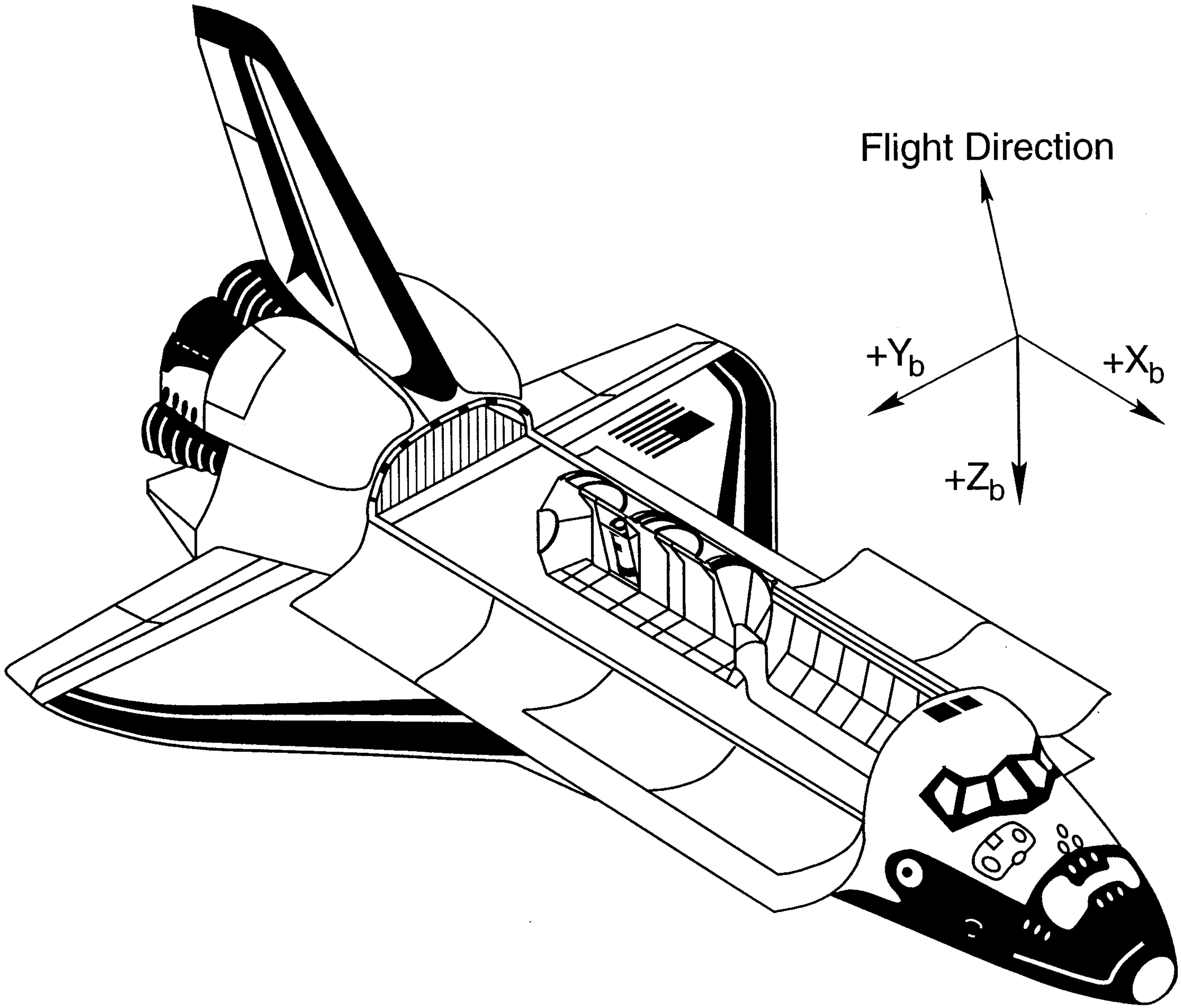


FIG. 1

# PAS Flight Deck Measurements Extrapolated to CGF Location

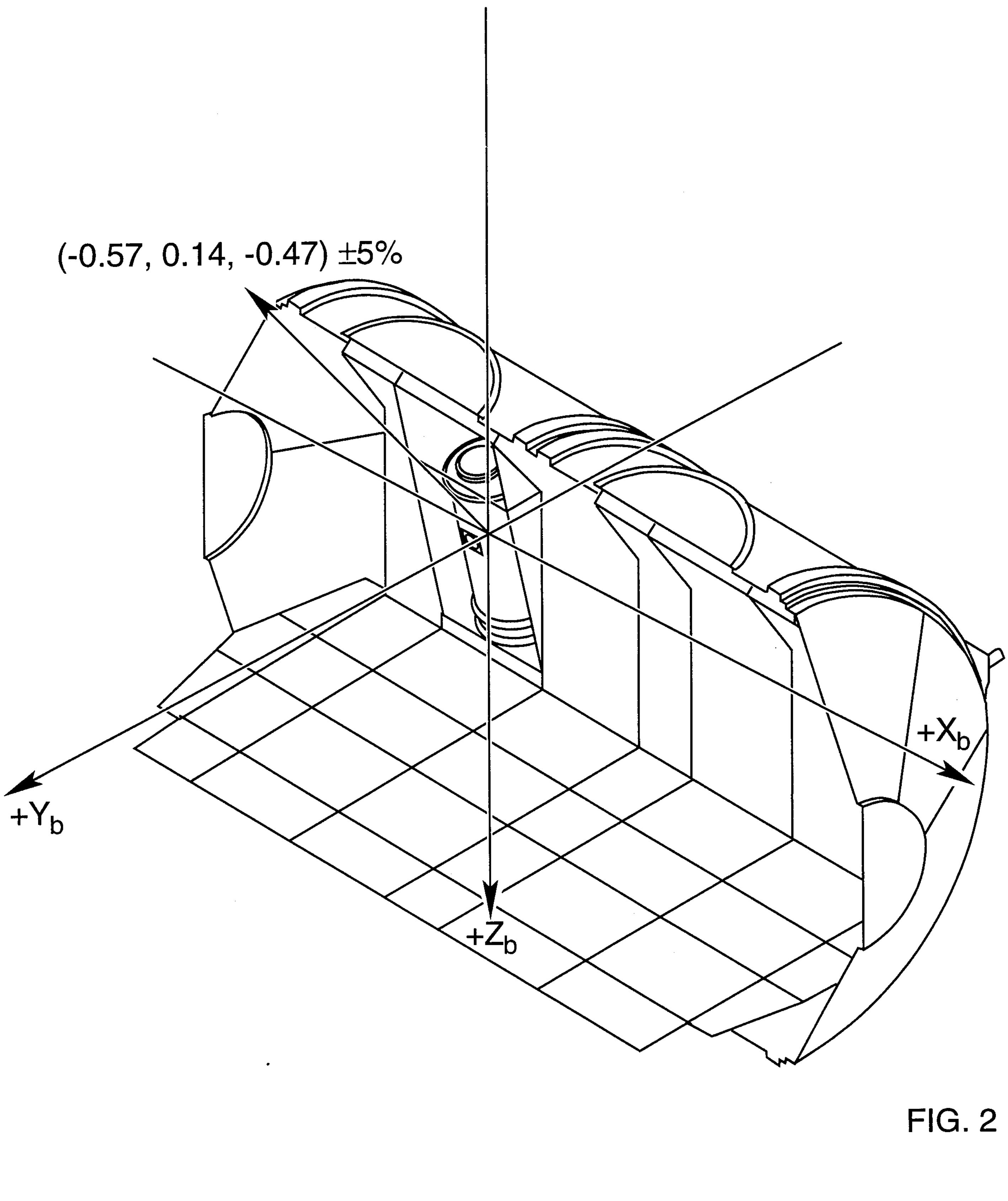


FIG. 2

# OARE Data Average with FES Off

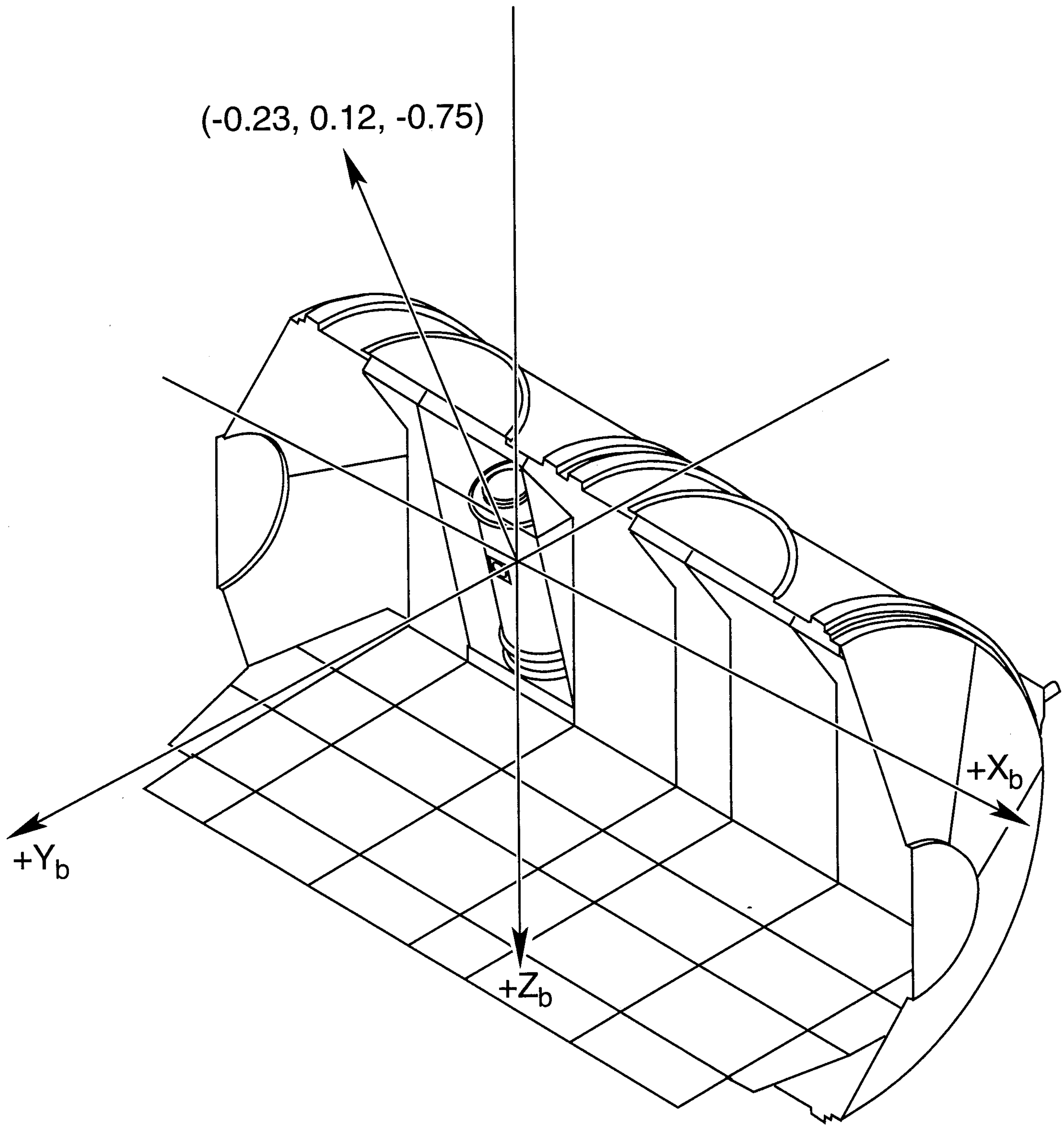


FIG. 3

# OARE Data Minimum with FES Off

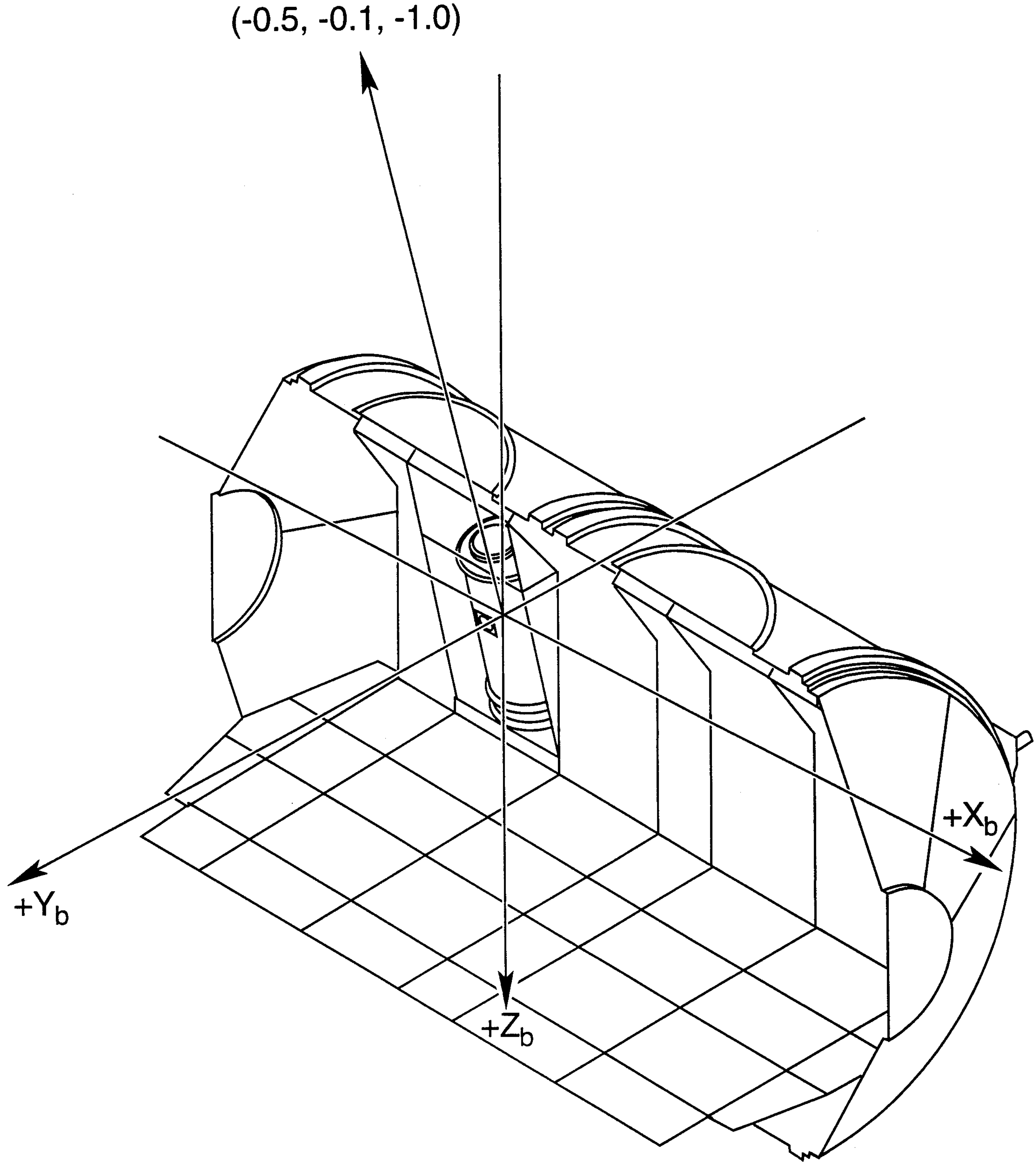


FIG. 4

# OARE Data Maximum with FES Off

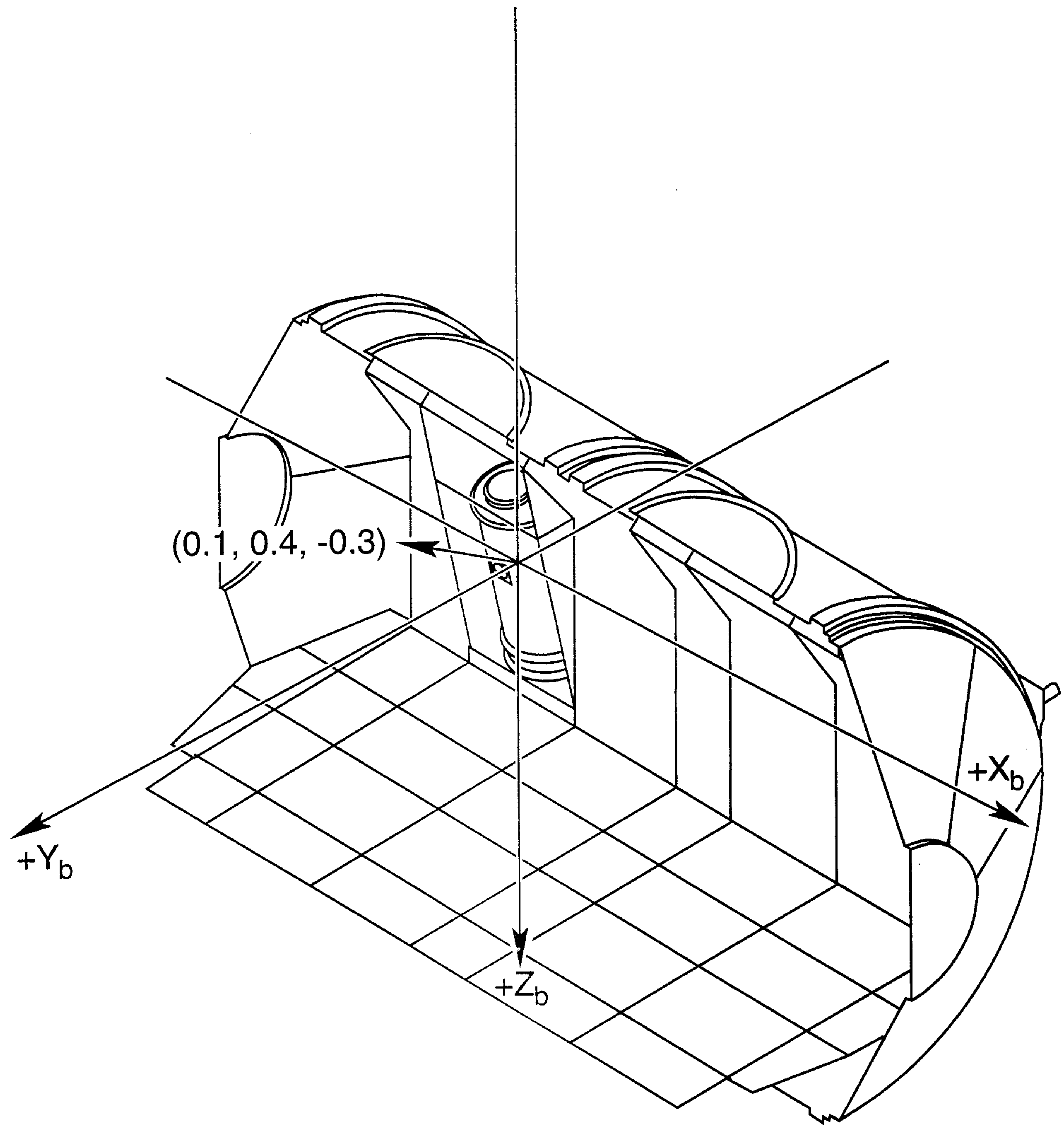


FIG. 5

# OARE Data Average with FES On

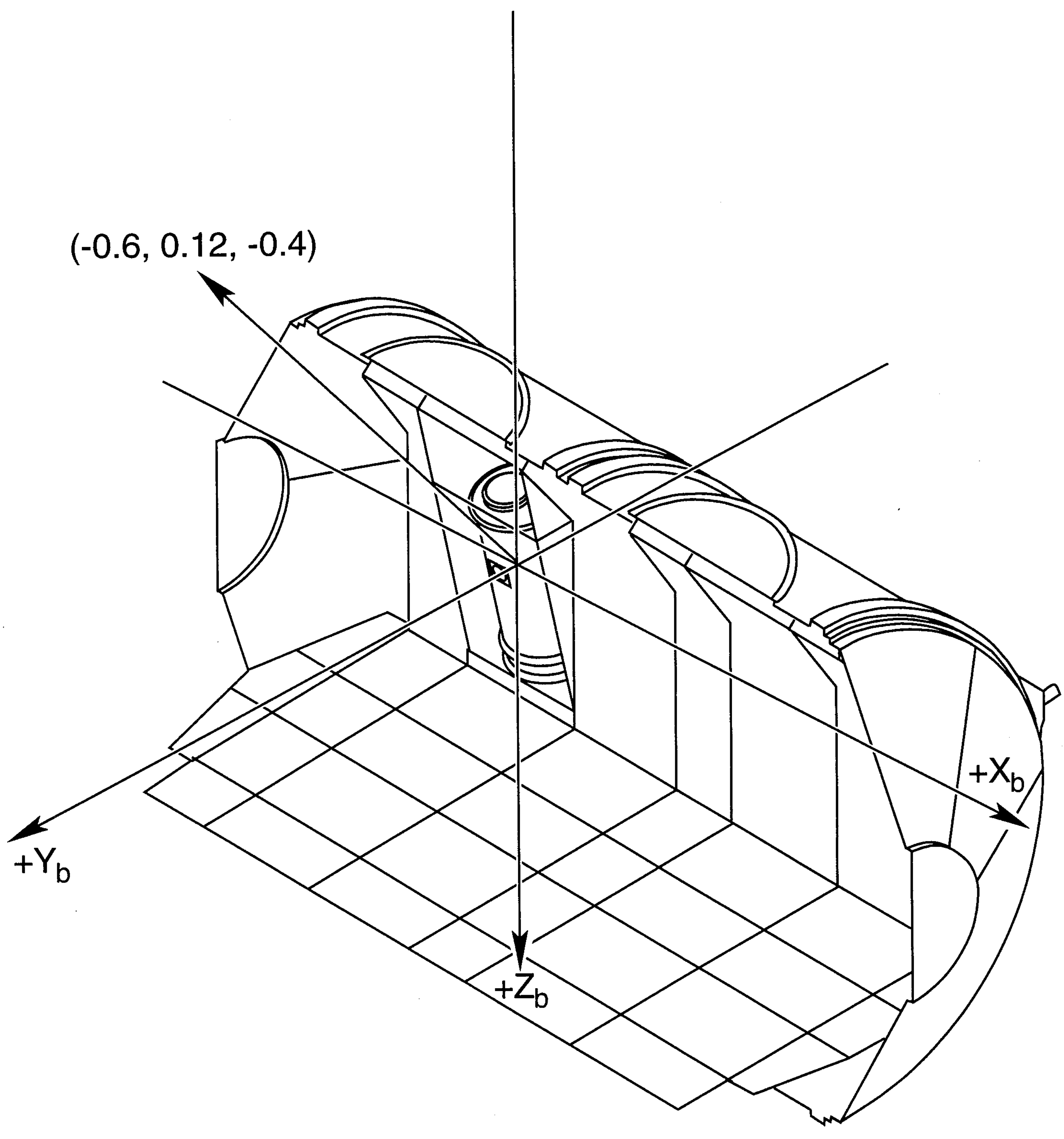


FIG. 6

# A Note on the Frame of Reference for Orbiter Accelerometer Measurements

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The microgravity environment of a spacecraft is a manifestation of the acceleration relative to the mass center of the spacecraft that is experienced by any object capable of motion independent of the spacecraft itself. To any observer in the spacecraft frame of reference this object will appear to undergo an acceleration relative to the spacecraft. Thus, since most microgravity experiments will have the spacecraft as a natural frame of reference the natural way to express the directionality of the microgravity acceleration is with respect to the spacecraft reference frame. It is important, however, to be aware that this is not always the natural frame of reference for an accelerometer. For example, many standard accelerometers measure the acceleration by finding the instantaneous force required to reposition a reference mass. This force will act opposite to the instantaneous acceleration relative to the spacecraft that is experienced by the reference mass. Since most science investigators interpret their experimental data in terms of the microgravity environment relative to the spacecraft frame of reference it is important that when data are presented that the frame of reference for the acceleration is specified.

For example, consider an Orbiter flying in airplane mode, nose into the velocity vector, working in the Orbiter body coordinate system ($+X_b$ points out the nose, $+Y_b$ points out the right wing, $+Z_b$ points out the belly). The Orbiter experiences atmospheric drag. Now consider a proof mass, a component of some experiment located within the Orbiter. As the Orbiter experiences drag, the proof mass accelerates in the $+X_b$ direction (that is, it moves forward with respect to an object fixed to the Orbiter). This is what investigators consider the response to the low-gravity environment of the orbiting laboratory. The conventional accelerometer, on the other hand, measures and records a negative acceleration ($-X_b$) because the Orbiter is slowing down due to drag (with respect to the proof mass).

Note that while both conventions are correct, some confusion has arisen from acceleration measurements taken during USML-1. The issue has not come up until now because the vibrational environment measured to date varies so much in direction that the difference has not been noticeable. The OARE was used on USML-1, however, "to measure and record the Shuttle aerodynamic acceleration environment from the free molecule flow regime through the rarefied flow transition into the hypersonic continuum regime." The acceleration regime measured by OARE is that generally referred to as quasi-steady. The major components of the quasi-steady regime are atmospheric drag, gravity gradient effects, and rotational (tangential and radial) accelerations. These components are of low enough frequency that differences between the reference frames in which they are referred to are noticeable.

Numerical modelling of low-gravity experiments is done to predict variations in experimental parameters caused by the low-gravity environment. Hence, the experiment/science reference frame is used in both the experiment modelling and the environment modelling. It is the difference between such modelled data (in the experiment/science reference frame) and the data recorded by OARE on USML-1 (reported in the accelerometer reference frame) that has led to some degree of confusion and an investigation into a "mysterious force" on USML-1.

The major differences between the modelled quasi-steady environment on USML-1 and the accelerations recorded by OARE can be explained by the different reference frames. For the experimenters who wish to know the low-gravity environment experienced by experiments on USML-1, the signs of OARE data need to be reversed. Note that the other differences ($\sim -4\times10^{-7}$ g in $X_b$ during a 90 minute period studied) between modelled data and OARE are real and can be accounted for by other low frequency disturbances such as FES operations that are not included in the model.